UDC 666.1.031

COOLING OF THE GIRD OF THE MELTING TANK OF A GLASSMAKING FURNACE

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Translated from *Steklo i Keramika*, No. 8, pp. 13 – 16, August, 2009.

The effect of the air cooling intensity on heat transfer through an electrofused AZS-girder of the side wall of the melting tank is investigated. It is shown that air cooling should be used throughout the entire furnace run.

Key words: glassmaking furnace, heat transfer, corrosion resistance of a refractory, furnace lifetime extension.

As a rule, the run time of a glassmaking furnace is limited by the stability of the lateral walls of the melting tank at the level of the molten glass surface. Many concepts of the mechanism of the corrosion of the electrofused baddeleyite corundum at the interface of the three phases (solid – liquid – gas) are in agreement that its solubility is the main reason why the refractory is corroded by molten glass [1]. Since the interaction of AZS-articles with glass melt is a heterogeneous process, which occurs at the interface of the solid and liquid phases, for high-viscosity molten glass the corrosion rate of the refractory will be determined by the transfer of matter into the reaction zone. Decreasing temperature at the contact boundary of the phases by cooling the outer surface of the refractory walls is one of the most accessible and effective methods for decreasing the rate of corrosion of the refractory material. Air and evaporative cooling (less often) are used for this purpose [2 – 6]. For purposes of designing and operating glassmaking furnaces, it is undoubtedly of interest to determine rational conditions for cooling the gird of the tank that ensure effective operation of the electrofused AZS-girders.

The effectiveness of air cooling the gird of the tank in a glassmaking furnace is examined in [1 – 4]. The temperature of the inner surface and the thermal conductivity of AZS-refractory were assumed to 1500°C and 4.1 W/(m · K), respectively. The heat transfer through the masonry was calculated for three values of the convective heat-transfer coefficient $\alpha_c = 12$, 180, and 360 W/(m^2 · K). The first value of α_c corresponds to the natural convection regime. The second value corresponds to forced air cooling with normative air flow rate $V_a = 0.8 – 1.0$ m^3/sec per 1 m of wall length and pressure 800 – 900 N/m^2 [1]. The computational method permits taking account of the thermal resistance of the molten glass near the wall [4].

One result obtained in [1, 2] is that the lowest rate of corrosion corresponds to the highest value $\alpha_c = 360$ W/(m^2 · K) attained with intense ventilation of the outer surface of the refractory wall, for example, by means of air-evaporative cooling [5]. It was also noted that forced air cooling is ineffective during the initial period of furnace operation (6 – 8 months). Such cooling has a positive effect on the corrosion rate of the refractory only for residual girder thickness equal to approximately 150 mm. On this basis the authors conclude that thinned-down girders (approximately 20 mm) should be placed on the top row of the melting tank wall, and when these girders wear down to a critical size (approximately 20 mm), plates of variable thickness (100 – 150 mm) should be superposed on them in order to reinforce the wall.

The dissolution of the refractory materials in the melt results in the appearance of a relatively thick boundary layer (up to 10 mm) [1].When this layer is cooled a thermal crust which impedes corrosion of the lining is formed. It is noted in [7] that a very important condition for the stability of the linings of tanks containing melt is ensuring that the multilayer wall is in a stationary thermal state. Depending on the physical wear of the refractory, heat transfer through a one-layer (refractory) or two-layer (refractory + crust) wall must be studied. In the first variant, the effect of the parameters of forced cooling of the outer surface of the girder on the girder's corrosion rate is not obvious. At the same time the cooling problem for a corundum girder can be formulated more concretely: if a crust forms directly on the refractory wall, then the temperature at the crust – wall contact surface must be kept at a level so that the wall does not interact with the refractory and does not form eutectic mixtures.

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We shall discuss in greater detail the choice of the variable parameter determining the effectiveness of air cooling. It is known that the relation between the temperature field in a solid body and the conditions of heat emission on its surface is characterized by the Biot number, which is directly proportional to the coefficient of convective transfer. Since α_c is found from the solution of a complicated criterial equation [8], we shall use as the variable quantity the rate w_a of air flow out of the cooling nozzle [9]. This parameter can be normalized, since it can be relatively easily calculated and measured experimentally. The air velocity ($w_a = 0 - 20$ m/sec) was used in [5] as a variable quantity in a study of air – evaporative cooling of a tank gird.

Let us consider the effect of the velocity of the cooling air ($w_a = 0 - 120$ m/sec) on the heat transfer through a new AZS-girder (41% ZrO_2) with thickness $S_{rw} = 150$ and 250 mm, placed in the fining zone. Let a glass layer form at the wall ($S_{wall} = 10$ mm) on the inner surface of the girder, and let the internal temperature for the layer equal the average temperature of the surface of the tank: $t_{int} = t_{wall} = 1415.3$°C [10]. We calculate the heat transfer through a two-layer wall with thickness $S = 160$ and 260 mm taking account of the temperature dependence of the thermal conductivity of the refractory ($\lambda = 8.84 - 11.9 \times 10^{-3}\, t + 7 \times 10^{-6}\, t^2$) and green molten glass ($\lambda_{eff} = 1.0908 - 0.5 \times 10^{-3}\, t + 6 \times 10^{-6}\, t^2$).

The computational results presented in Fig. 1 show that in the given range of variation of the air velocity ($w_a = 0 - 120$ m/sec) a smaller initial thickness of the girder is characterized by higher heat emission into the surrounding medium. For the conditions of natural convection ($w_a = 0$) the heat flux equals 22,633 W/m^2 (row 5), which is 52.5% higher than for $S_{rw} = 250$ mm (row 1). For forced convection ($w_a > 0$ m/sec) this difference becomes even larger. Analysis of the dependence of the heat flux into the surrounding medium on the velocity of the cooling air $q_{ext}(w_a)$ for $S_{rw} = 250$ mm, shows that the range $w_a = 0 - 40$ m/sec is characterized by a large increase of the heat emission into the surrounding medium ($q_{ext} = 14{,}842 \to 19{,}157$ W/m^2) and decrease (row 3) of the external temperature of the refractory wall ($t_{ext} = 430.7 \to 147.5$°C). As the air velocity increases further ($w_a = 40 - 120$ m/sec), q_{ext} and t_{ext} change by smaller amounts: $19{,}157 \to 20{,}195$ W/m^2 and $147.5 \to 90.9$°C, respectively. We note that $\alpha_c = 180$ W/(m$^2 \cdot$ K) is reached for $w_a = 40.54$ m/sec ($V_a = 0.81$ m^3/sec). For $S_{rw} = 150$ mm the coefficient of convective heat emission $\alpha_c = 180$ W/(m$^2 \cdot$ K) corresponds to $w_a = 32.55$ m/sec and $V_a = 0.62$ m^3/sec. For the normative air flow rate 0.81 m^3/sec the coefficient of convective heat emission is 206.4 W/(m$^2 \cdot$ K).

The character of the change in the dependence $\alpha_c(w_a)$ attests to the fact (see Fig. 1, rows 4 and 8) that its form is at variance with the functions $q_{ext}(w_a)$ and $t_{ext}(w_a)$. It is known that heat emission into the surrounding medium is determined by the coefficient of heat transfer through a multilayer

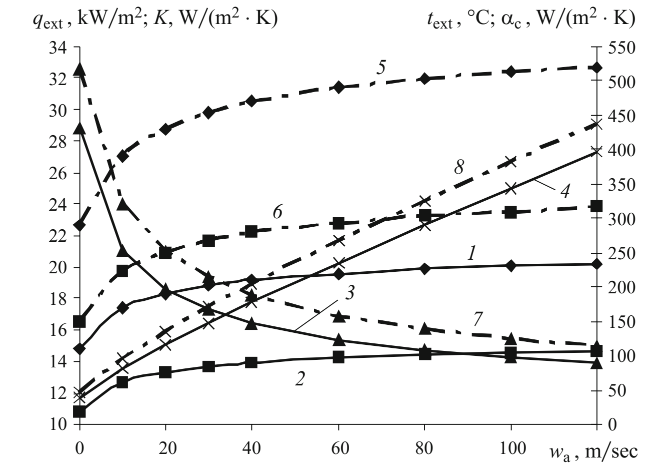

Fig. 1. Effect of the air velocity on the heat flux (*1*, *5*), the heat-transfer coefficient (*2*, *6*), the external temperature of the gird (*3*, *7*), and the coefficient of convective heat emission (*4*, *8*). The numbers on the curves correspond to the row numbers: *1 – 4* and *5 – 8*) $S_{rw} = 250$ and 150 mm.

wall (rows 2 and 6). At the same time the complex character of this coefficient does not permit using it to normalize the effectiveness of air cooling. Thus, the velocity and specific flow rate of the cooling air can be taken as objective normalizable parameters for the purpose of designing the gird cooling system.

The data in Fig. 1 do not give any basis for asserting that thinned girders should be used for the refractory side wall of the melting tank. The high level of the heat losses during the initial period of operation of the furnace is not compensated by the supposed decrease of the corrosion rate of the refractory as a result of the lower (by 6.4°C for natural cooling) temperature of the contact surface between the refractory and the near-wall layer. At the same time, at this stage of the analysis one must agree that the forced cooling of a new 250 mm thick wall is ineffective. The change $w_a = 0 \to 40.54$ m/sec results in a decrease of the temperature at the location of the contact between the layers from 1403.2 to 1399.7°C and 29.2 % higher heat losses. For the highest rate of cooling ($w_a = 120$ m/sec) as compared with natural ventilation the indicated temperature decreases by only 4.4°C, while the heat flux increases by 36.1%.

Now let us consider the effect of forced cooling on the parameters of heat transfer through a corroded girder with residual thickness 200, 150, 100, 50, and 25 mm (0.8, 0.6, 0.4, 0.2 and $0.1S_{rw}$). We shall assume that the corrosion cavity in the refractory is filled with molten glass and that the thickness of the molten glass layer corresponds to its wear (50 – 225 mm). The boundary condition with respect to the inner temperature of the glass layer corresponds to $t_{in} = t_{wall} = 1415.3$°C. We shall evaluate the effectiveness of the cooling according to the temperature t_s at the contact boundary between the glass and the corrosion cavity of the girder and the heat flux into the surrounding medium.

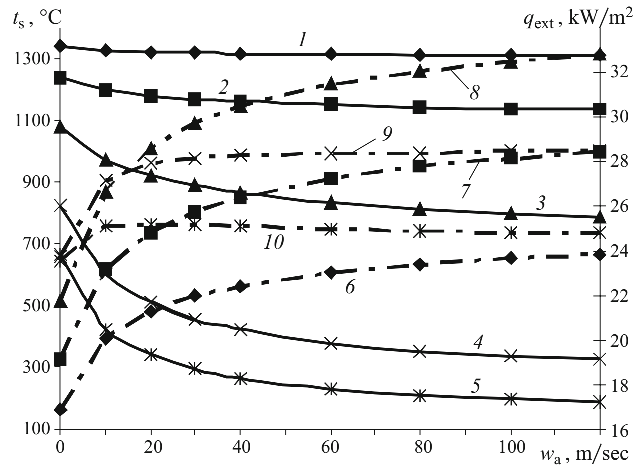

Fig. 2. Effect of the air velocity on the temperature in the contact plane of the near-wall layer of the glass and refractory (*1 – 5*) and the heat flux into the surrounding medium (*6 – 10*) with residual girder thickness 0.8 (*1*, *6*), 0.6 (*2*, *7*), 0.4 (*3*, *8*), 0.2 (*4*, *9*), and $0.1S_{rw}$ (*5*, *10*). The numbers on the curves correspond to the row numbers.

The data in Fig. 2 show that the effect of the air velocity on the change of the indicated parameters largely depends on the size of the corrosion cavity in the refractory. For minimal wear of the girder (50 mm) and natural convection on the outer surface of the refractory the temperature drop along the glass layer in the corrosion cavity is $t_{in} - t_s = 71.4$°C. At the same time a change of air velocity in the range 0 – 120 m/sec decreases t_s by only 31.7°C (row 1). The heat losses increase by 41.4%. Air cooling with $S_{rw} = 150$ mm (Fig. 2) is just as ineffective. The range of the residual thickness of the refractory 100 – 25 mm (rows 3 – 5) is characterized by a substantial decrease of t_s with natural as well as forced convection on the outer surface of the girder. For $w_a = 0$ the convective temperature decreases from 1415.3 to 1082.4, 826.1, and 665.4°C, respectively, for $S_{rw} = 100$, 50, and 25 mm. Forced cooling of the refractory with air velocity $w_a = 40$ m/sec decreases t_s to 865.4, 421.8, and 265.4°C. Thus, conditions for a thermal crust to form are created at the contact boundary between the media right up to the lining slag layer of the molten glass.

The change of the heat flux into the surrounding medium as a result of the wear of the refractory and the cooling rate of its outer surface (see Fig. 2) is of practical interest. For natural convection a change of the residual thickness of the girder from 250 to 50 mm results in an increase of q_{ext}, on average, by 0.3% per 1 mm of wear. The change $S_{rw} = 50 \to 25$ mm is characterized by a decrease of q_{ext} by 0.038%/mm. For forced convection on the outer surface of the refractory the function $q_{ext}(w_a)$ is also determined by the magnitude of its wear. For $S_{rw} = 250 \to 100$ mm (rows 6 – 8) an increase of the air velocity ($w_a = 0 - 120$ m/sec) intensifies heat emission into the surrounding medium. For $S_{rw} = 50$ mm (row 9) and $w_a \to 20$ m/sec the increase in q_{ext} is negligible, and for $S_{rw} = 25$ mm (row 10) and $w_a = 10 \to 120$ m/sec the heat flux decreases by 1.37%.

In summary, the choice of the velocity of the cooling air is determined by the wear of the refractory, whose magnitude cannot be measured directly. In this connection, it is helpful to consider the temperature of the outer surface of the girder, whose experimental determination during the entire furnace run is a technically solvable problem. In [9] the temperature of the outer surface of the refractory was taken to be 100°C. Maintaining such a low value of t_{ext} with the variation along the tank $t_{ext} = t_{wall} = 1200 - 1500$°C presupposes high-velocity cooling of the gird ($w_a \to 100$ m/sec). The data in Figs. 1 and 2 show that practically speaking the condition $t_{ext} = 100$°C is too extreme and can be adjusted upward. It follows from the data in Fig. 2 (rows 4 and 5) that the air velocity can be limited by 40 m/sec, above which its effect on the temperature t_s of the contact surface between the media becomes negligible. The indicated velocity corresponds to $t_{ext} = 181.4$ and 170.1°C (masonry wear 0.8 and $0.9S_{rw}$). We shall use the average value $t_{ext} \approx 175$°C.

The conditions $t_{in} = t_{wall} = \text{const}$ and $t_{ext} = \text{const}$ as a function of the wear of the refractory can be satisfied simultaneously by means of different intensity of the convective heat transfer on the outer surface of the gird. The parameters of heat transfer through the electrofused AZS-gird ($t_{in} = t_{wall} = 1415.3$ and $t_{ext} = 175$°C) are presented in Table 1. The highest air velocity does not exceed 50 m/sec, which corresponds to its normative flow rate 1.0 m^3/sec per 1 m of wall length. Maintaining a two-layer wall in a stationary thermal state during the entire service life of the furnace by controllable external cooling creates conditions for slowing the corrosion of the refractory. Even though for Biot number > 5 the heat transfer through the wall is mainly determined by the inner thermal resistance (of the crust and refractory), the positive role of the external resistance ($1/\alpha_c$) manifests as a possibility of creating controllable stationary thermal operating conditions for the masonry. Hence follows the conclusion that air cooling of the gird of a melting tank throughout the entire run of a glassmaking furnace is helpful.

TABLE 1.

Parameter	Residual thickness of refractory, mm					
	250*	200	150	100	50	25
w_a, m/sec	26.7	32.5	39.9	47.6	43.2	37.7
t_s, °C	1400.1	1320.4	1161.7	851.4	413.1	271.1
α_c, W/(m$^2 \cdot$ K)	138.0	163.2	195.3	228.9	209.6	185.8
q_{ext}, kW/m^2	18.66	22.07	26.39	30.94	28.30	25.10
Biot number	9.052	8.455	7.306	4.997	1.764	0.711

* Taking account of the near-wall 10 mm thick layer of glass.

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